AD 713 521

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J. L. Drake, et al

Army Engineer Waterways Experiment Station
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1970

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J. L. DRAKE AND A. SAKURAI
U. S. Army Engineer Waterways Experiment Station
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INTRODUCTION

Since the advent of nuclear weapons, the investigation of the ground shock effects from these devices has been the subject of much research. Reliable methods for estimating the stresses and the ground motions transmitted from a postulated nuclear detonation through earth materials are necessary for the cost effective design of hardened strategic systems.

Methods currently employed for the evaluation of ground shock effects are generally inadequate from the standpoint of the system designer. Computer code simulations are designed to predict the history of ground motion from the initial moment of the explosion, thus requiring an elaborate description of the characteristics of the material under high pressure and temperature. Because of their complexity, the extension of a numerical calculation into the range beyond the close-in field is costly and often unreliable due to the accumulating errors of the approximation. Empirically determined formulae, derived from scaled high explosive and past nuclear test events, are more generally used to provide quantitative description for specific weapons effects conditions; however, these formulae often cannot be extended to account for varying geometry of bursts and changes in the earth properties.

This situation is further complicated by the fact that the shock wave from a surface burst preserves the close-in characteristics of the individual explosion throughout the entire range of interest. Thus, slight deviations in the input values from the idealization of the real environment can result in seemingly unrealistic results. The sensitivity of the solution to variations in the source description can be mathematically related to a singularity of the solution at the origin.

This paper describes an attempt to improve the situation by utilizing a simple model which is adequate to describe the salient features of the ground motion history outside the close-in range. It is essential, to this purpose, to recognize the fact that the elastic

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solution cannot account for the behavior near the explosion source and that the close-in effects are taken into account by an appropriate fit of the singularity of the solution. This approach is justified when these effects are confined to a small region in space and thus provides the key to the analysis.

SOLUTION FOR THE CONTAINED BURST

Ground shock effects research has centered around the fully contained underground weapons testing because of limitations on testing in the atmosphere. The analytical solution for the contained explosion is studied to provide a simple check case for verification of the elastic model and to determine the experimental scale factors required for fitting the close-in effects. Since the particle motion is most frequently measured in underground experiments, the particle velocity parameter will be used in this study.

The general solution for spherically diverging waves in an elastic medium expressed in terms of the particle velocity $\dot{u}(r,t)$ is (1)

$$\dot{u}(r,t) = \frac{c}{r^2}\left[F(r - ct) - rF'(r - ct)\right] \qquad (1)$$

where r is the distance from the origin, t is time, and c is the dilatational wave velocity. $F(r - ct)$ is an arbitrary function of the argument $(r - ct)$. A prime denotes a derivative with respect to the argument and a dot denotes a derivative with respect to time.

Applications of this solution to waves generated by explosions were studied by a variety of authors (1,2). The explosion is commonly modeled by applying a pressure to the surface of a spherical cavity. The results are generally found to be inadequate for describing weapons effects because the far field solution predicts spatial peak attenuations of nearly r^{-1} whereas measurements show rates of about r^{-2} .

A close examination of Equation 1 shows that by simply specifying the arbitrary function $F(r - ct)$ in a proper form, the first term (r^{-2} term) of the solution can be made to dominate and thus provide an expression that at least describes the peak values of an experiment correctly. The function $F(r - ct)$ was chosen as

$$F(r - ct) = Ae^{-\left[\frac{\alpha}{c}\left(t - \frac{r}{c}\right)\right]^2} \qquad (2)$$

because of its simple form and fit to the measurements. The final expression for particle velocity is then

$$\dot{u}(r,t) = \frac{Ac}{r^2}\left(1 - \frac{2\alpha^2\tau r}{c}\right)e^{-\alpha^2\tau^2} \qquad \tau = t - \frac{r}{c} \geq 0 \qquad (3)$$

where A and α are quantities to be determined that are characteristic of the source. The peak particle velocity occurs at $\tau = 0$

and attenuates as r^{-2} which is consistent with measurements. The wave form is an exponential which agrees with the typical pulse determined by weapons testing.

Conventional cube root scaling is introduced into Equation 3 without changing its dimensions in order to determine the variation with the weapon yield W. Equation 3 becomes

$$\dot{u}(r_o, t_o) = \frac{A_o c}{r_o^2}\left(1 - \frac{2\alpha_o^2 \tau_o r_o}{c}\right) e^{-\alpha_o^2 \tau_o^2} \tag{4}$$

where

$$A = A_o W^{1/3} \ , \ r = r_o W^{1/3} \ , \ \tau = \tau_o W^{1/3} \ , \ \alpha = \alpha_o W^{-1/3}$$

The weapon parameters A_o and α_o are easily determined from the scaled field measurements by noting

$$A_o = \frac{\dot{u}_{max}\, a_o^2}{c} \qquad \alpha_o = \frac{c}{2a_o \tau_o^+} \tag{5}$$

where $\dot{u}_{max}$ is the maximum particle velocity and τ_o^+ is the positive duration of a measured wave at the scaled range $r_o = a_o$. Evaluations of A_o and α_o show that they are constants not depending on test material or weapon yield.

A comparison between the wave form calculated by Equation 4 and a wave form from the Salmon (5 kt) (3) event in a salt medium is shown in Figure 1. The elastic calculation necessarily has an abrupt rise on the initial portion because of the need to make $F(r - ct)$ dominate its derivative in the neighborhood of the peak value. The peak particle velocity calculated using constant A_o is compared with several nuclear bursts in a variety of earth materials in Figure 2.

SOLUTION FOR THE SURFACE BURST

The object of this section is to utilize the classical linear elastic model for the prediction of the characteristics of the ground shock waves generated by explosions at the surface of the earth. The use of this model for this purpose has not been fully explored because of the lack of an adequate analytical solution to be utilized. Since the mathematical problem of the explicit solution of the surface burst explosion is very difficult, even for the simplest model of linear elasticity, the existing analytical solutions to this problem are either incomplete or unrealistic for all practical purposes; thus, a more realistic and explicit solution had to be developed. It is essential, to this purpose, to recognize the fact that the solution of the surface burst problem is very sensitive to the input conditions. Mathematically, this sensitivity is related to the singularity of the solution at the explosion source, and the

solution, to be useful, should be constructed such that the singularity properly represents the characteristics of the source.

Consider the displacement potentials φ and ψ determined from the wave equations

$$\frac{\partial^2 \varphi}{\partial t^2} = c^2 \Delta\varphi \quad , \quad \frac{\partial^2 \psi}{\partial t^2} = c_s^2 \Delta\varphi \tag{6}$$

with propagation velocities c and c_s of the compressional and shear waves and $\Delta = \frac{\partial^2}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)$ using the cylindrical coordinate system r and z with axial symmetry. The formal solution of Equation 6 to the surface burst problem can be obtained in the form of the double integral of the Laplace-Hankel transforms. The direct derivation of the explicit expression of φ and ψ from this formal solution is difficult for the general region of $r > o$, but it can be obtained on the axis $r = o$ in the following asymptotic expansion form:

$$\varphi \sim \frac{a_1}{z} + \frac{a_2}{z^2} + \ldots \quad , \quad \psi \sim \frac{b_1}{z} + \frac{b_2}{z^2} + \ldots \tag{7}$$

where a_i and b_i $(i = 1,2,\ldots)$ are functions of $t - \frac{z}{c}$ and $t - \frac{z}{c_s}$ respectively and are determined from the characteristics of an individual input source condition. Equation 7 exhibits the nature of the singularities on the input source.

Approximate expressions for φ and ψ for $r > o$ are constructed from the sum of the elementary solutions of the wave equation which have singularities at the origin that are matched to the solution (Equation 7) above are

$$\begin{aligned} \varphi &\sim \frac{\varphi_1\left(t - \frac{R}{c}\right)}{R} + \frac{\partial}{\partial z}\frac{\varphi_2\left(t - \frac{R}{c}\right)}{R} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\frac{\varphi_3\left(t - \frac{R}{c}\right)}{R}\right) + \ldots \\ \psi &\sim \frac{\psi_1\left(t - \frac{R}{c_s}\right)}{R} + \frac{\partial}{\partial z}\frac{\psi_2\left(t - \frac{R}{c_s}\right)}{R} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\frac{\psi_3\left(t - \frac{R}{c_s}\right)}{R}\right) + \ldots \\ R &= \left(r^2 + z^2\right)^{1/2} \end{aligned} \tag{8}$$

where φ_i and ψ_i $(i = 1,2,\ldots)$ are determined from a_i and b_i $(i = 1,2,\ldots)$ by comparing the terms with the same powers in z at $r = o$ with those in Equation 7. The horizontal and vertical displacements u and v are then determined by

$$u = \frac{\partial \varphi}{\partial r} + \frac{\partial^2 \psi}{\partial r \partial z} \quad , \quad v = \frac{\partial \varphi}{\partial z} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial \psi}{\partial r}\right) \tag{9}$$

The accuracy of the approximation depends upon how many terms are retained in Equation 8. The result of the application of this method to the simpler case of the liquid half-space with only one wave shows good agreements with experimental data is attained with two terms of the approximation formula (4). A cursory examination of the elastic case with two terms of the approximation is being made and compared with test data for rock environments. The results of this correlation are shown in Figure 3, where the horizontal accelerations $\ddot{u}$ near the surface are compared with the MINE ORE (5) high explosive test data.

CONCLUSIONS

General formulae for the ground motions from an explosion source were derived and their results compared with high explosive and nuclear weapons test data. The comparisons show reasonably good agreement may be obtained by using a simple elastic description for the earth as long as the explosion is properly modeled.

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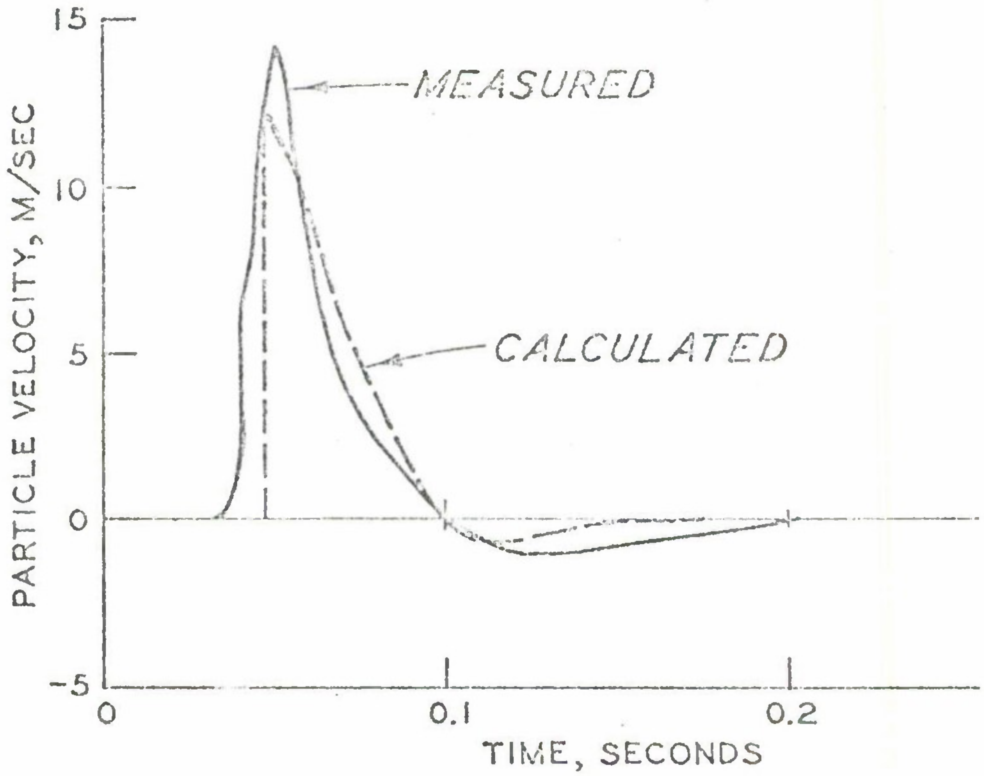

Fig. 1. Comparison of calculated particle velocity-time history with test data from Event SALMON at $r = 166$ meters

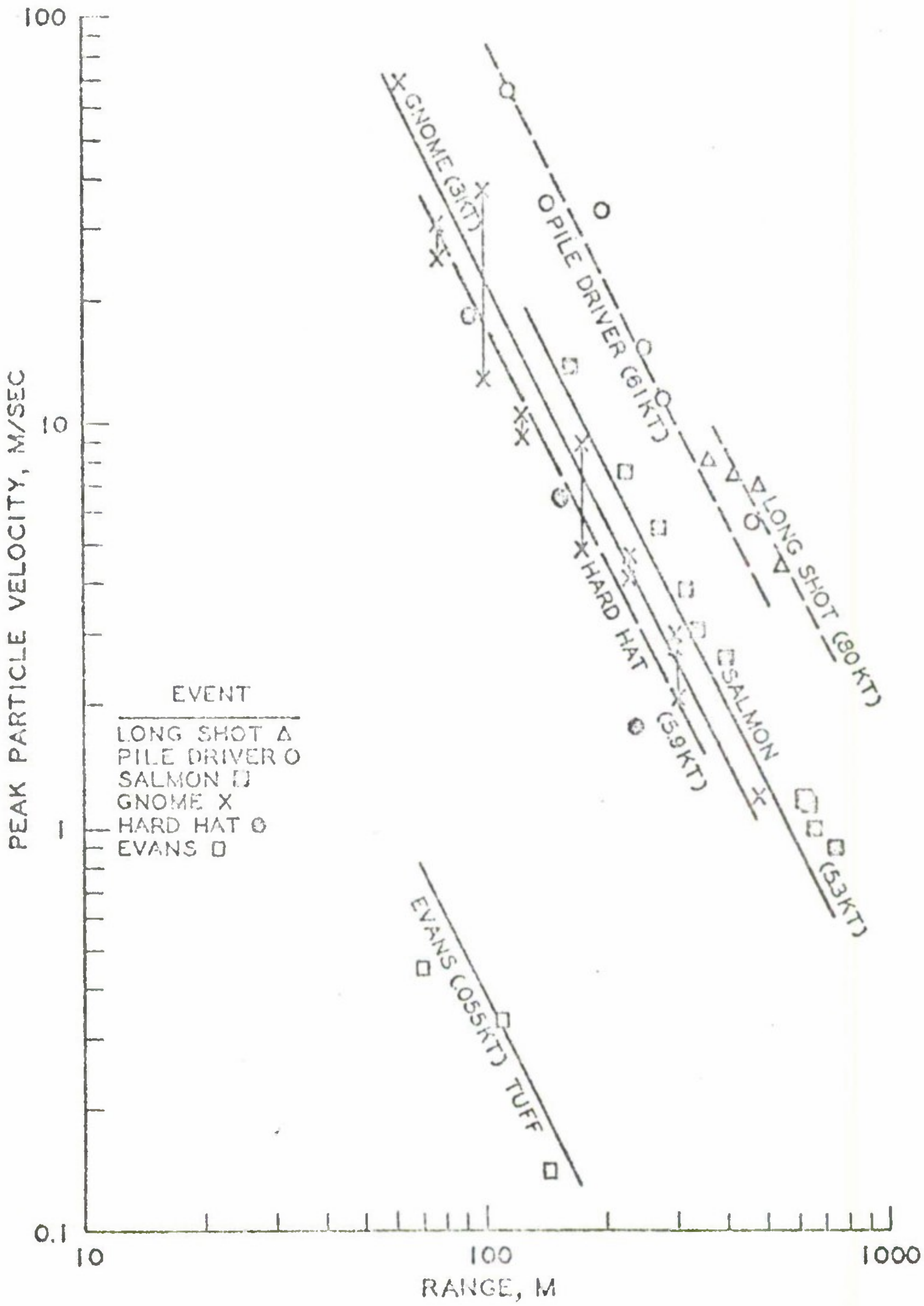

Fig. 2. Comparison of calculated peak particle velocity with test data from nuclear events in rock

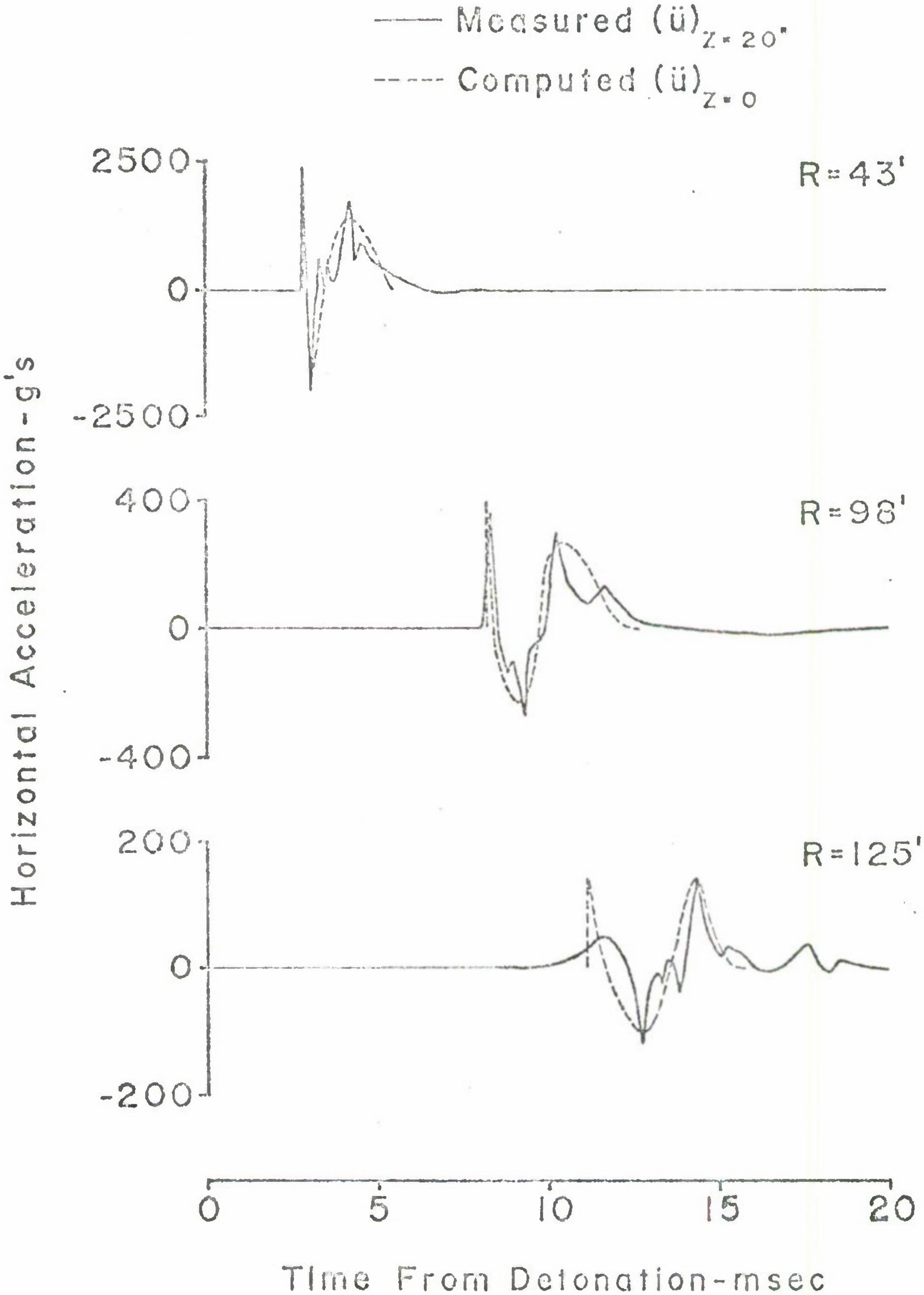

Fig. 3. Comparison of calculated horizontal acceleration-time history with test data from MINE ORE Event, MINE SHAFT Series